Neutrinoless double beta decay potential in a large mixing angle world *

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Abstract. We discuss the possibility of reconstructing the neutrino mass spectrum from the complementary processes of neutrino oscillations and double beta decay in view of the new data of Super-Kamiokande presented at the Neutrino2000 conference. Since the large mixing angle solution is favored, now, the prospects to observe double beta decay and provide informations on the absolute mass scale in the neutrino sector have been improved.

1 Double Beta decay and neutrino oscillations

Neutrinos finally have been proven to be massive by atmospheric and solar neutrino oscillation experiments. However, the absolute scale of neutrino masses, a necessary ingredient for reconstructing beyond the standard model physics, is still unknown, since informations obtained in neutrino oscillation experiments regard the mass squared differences and mixing angles, only. Only *both* neutrino oscillations and neutrinoless double beta decay *together* could solve this absolute neutrino mass problem [1,2,3]. In this paper we discuss the most recent data , as presented by the Super-Kamiokande Collaboration at the Neutrino2000 conference [4]. The small mixing angle solution for solar neutrinos is ruled out, now, at 90 % C.L. Moreover, solutions including sterile neutrinos seemed to be disfavored both for atmospheric as well as for solar neutrinos. In the following we thus will restrict ourselves to a three neutrino framework, omitting the LSND anomaly. (For a discussion of the small mixing angle solution and four neutrino scenarios see [1]). A global analysis in a three neutrino framework yield the following favored regions [5,6]:

- Solar neutrino oscillations favor $\nu_e - \nu_{\not e}$ oscillations within the large mixing angle (LMA) MSW solution:
  $\Delta m^2_\odot = 3\ (1-10)\cdot 10^{-5}\ \mathrm{eV}^2$
  $\tan^2\theta_\odot = 0.5\ (0.2-0.6)$,
  where the bestfit is given with the 90 % C.L. region in the brackets.
  Also a small region in the QVO(quasi-vacuum-oscillation)-LOW regime at

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$\Delta m^2_\odot = 10^{-7}$ eV^2, $\tan^2\theta_\odot = (0.6-0.8)$ is still allowed at 90 % C.L., while disfavored compared to the small and large mixing solutions in an analysis of the neutrino energy spectra of supernova 1987A [7].
- Atmosheric neutrino oscillations are solved by $\nu_\mu - \nu_\tau$ oscillations with: $\Delta m^2_{atm} = 3\ (1.6-5)\cdot 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} > 0.85$.

Neutrinoless double beta ($0\nu\beta\beta$) decay

$$ {}^A_Z X \rightarrow^A_{Z+2} X + 2e^- \tag{1}$$

has been shown to be a sensitive tool both for physics beyond the standard model [8,9] as well as for the reconstruction of the neutrino mass spectrum [1]. The most stringent limit is obtained from the Heidelberg–Moscow experiment [10],

$$\langle m\rangle = 0.27 \text{ eV} \quad (68\%\text{C.L.}). \tag{2}$$

Future experiments such as CUORE [11], MOON [12] and EXO [13] and GENIUS [14] aim at sensitivities down to 10^{-2} - 10^{-3} eV.

The observable measured in the mass mechanism of $0\nu\beta\beta$ decay is the ee element of the neutrino mass matrix in flavor space, the effective neutrino mass

$$\langle m\rangle = |\sum U^2_{ei} m_i|, \tag{3}$$

where U_{ei} denote the elements of the neutrino mixing matrix. For the three-neutrino case we get

$$\langle m\rangle = |m^{(1)}_{ee}| + e^{i\phi_2}|m^{(2)}_{ee}| + e^{i\phi_3}|m^{(3)}_{ee}|\ , \tag{4}$$

where $m^{(i)}_{ee} \equiv |m^{(i)}_{ee}|\exp{(i\phi_i)}$ $(i=1,2,3)$ are the contributions to $\langle m\rangle$ from individual mass eigenstates, which can be written in terms of oscillation parameters as:

$$|m^{(1)}_{ee}| = |U_{e1}|^2 m_1, \tag{5}$$

$$|m^{(2)}_{ee}| = |U_{e2}|^2\sqrt{\Delta m^2_{21} + m_1^2}, \tag{6}$$

$$|m^{(3)}_{ee}| = |U_{e3}|^2\sqrt{\Delta m^2_{32} + \Delta m^2_{21} + m_1^2}, \tag{7}$$

and ϕ_i are the relative Majorana CP-phases. The contributions $m^{(i)}_{ee}$ can be illustrated as vectors in the complex plane (fig. 1).

Some of the parameters in eq. 7 can be fixed or restricted from neutrino oscillation data: In the case of normal hierarchy Δm^2_{21}, $|U_{e1}|^2 = \cos^2\theta_\odot$ and $|U_{e2}|^2 = \sin^2\theta_\odot$ can be obtained from solar neutrinos, Δm^2_{32} from atmospheric neutrinos and $|U_{e3}|^2$ is restricted from experiments searching for electron disappearance such as CHOOZ. For inverse hierarchy one has to exchange neutrinos $\nu_1 \leftrightarrow \nu_3$ in the equations. The phases ϕ_i and the mass of the lightest neutrino, m_1, are free parameters. Thus the search for neutrinoless double beta decay

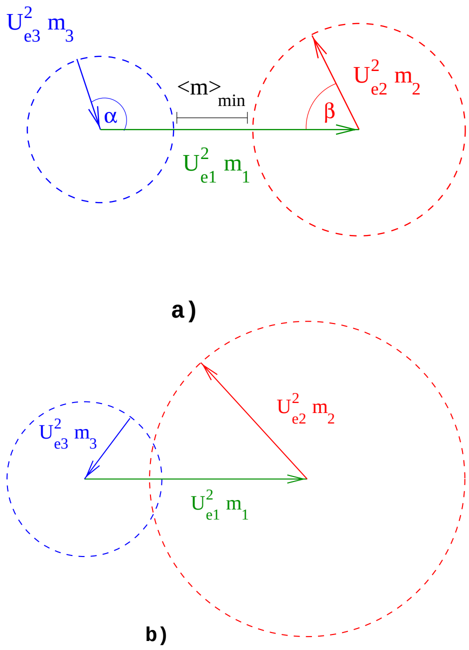


Fig. 1. The effective Majorana mass $\langle m\rangle$ in the complex plane. Vectors show contributions to $\langle m\rangle$ from individual eigenstates. The total $\langle m\rangle$ appears as the sum of the three vectors. Allowed values of $\langle m\rangle$ correspond to modulies of vectors which connect two points on the circles. Here $\alpha = \phi_3 - \pi$, $\beta = \pi - \phi_2$. a). $|m_{ee}^{(1)}| > |m_{ee}^{(2)}| + |m_{ee}^{(3)}|$: the vectors $\boldsymbol{m}_{ee}^{(i)}$ can not form a triangle and no complete cancellation occurs. b) $|m_{ee}^{(1)}| \leq |m_{ee}^{(2)}| + |m_{ee}^{(3)}|$: in this case complete cancellation occurs in the intersection points of the circles, so that $\langle m\rangle = 0$. (from [1]).

can provide informations about the neutrino mass spectrum and the absolute mass scale. With increase of m_1 the level of degeneracy of the neutrino spectrum increases and we can distinguish the extreme cases of hierarchical spectra, $m_1^2 \ll \Delta m_{21}^2 \ll \Delta m_{31}^2$ and degenerate spectra $\Delta m_{21}^2 \ll \Delta m_{31}^2 \ll m_1^2$. In the following we discuss these extreme cases as well as transition regions in detail, and comment on the case of inverse hierarchy.

2 Hierarchical spectra

Hierarchical spectra (fig. 2)

$$m_1 \ll m_2 \ll m_3 \tag{8}$$

can be motivated by analogies with the quark sector and the simplest see-saw models. In these models the contribution of m_1 to the double beta decay observable $\langle m\rangle$ is small. The main contribution is obtained from m_2 or m_3, depending on the solution of the solar neutrino deficit.

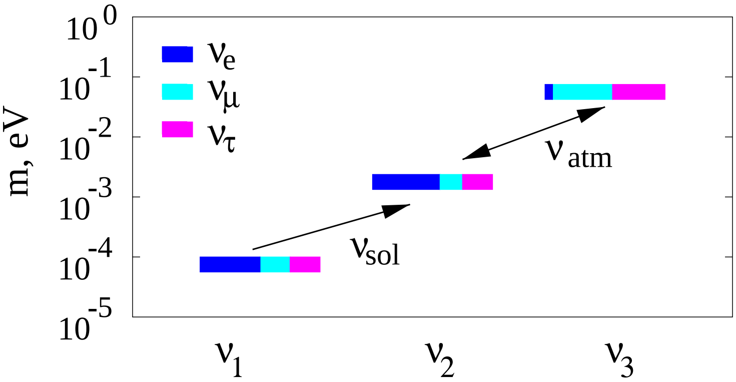


Fig. 2. Neutrino masses and mixings in the scheme with mass hierarchy. Coloured bars correspond to flavor admixtures in the mass eigenstates ν_1, ν_2, ν_3. The quantity $\langle m\rangle$ is determined by the dark blue bars denoting the admixture of the electron neutrino U_{ei}.

After *Neutrino2000*, the prospects of a positive signal in double beta decay are more promising, now. If the large mixing solution of the solar neutrino deficit is realized, the contribution of m_2 becomes dominant due to the almost maximal U_{e2} and the relatively large Δm^2_{21}:

$$\langle m\rangle \simeq m_{ee}^{(2)} = \frac{\tan^2\theta}{1+\tan^2\theta}\sqrt{\Delta m^2_{\odot}}. \qquad (9)$$

Fig. 3 shows values of $\langle m\rangle$ in the range of the large mixing angle solution. The closed lines denote the regions allowed at 90 % C.L. and 99 % C.L. according to [5]. In the 90 % C.L. region the prediction for $\langle m\rangle$ becomes definite, now,

$$\langle m\rangle = (1-3)\cdot 10^{-3}\ \mathrm{eV}. \qquad (10)$$

A coincident measurement of $\langle m\rangle$ at this order of magnitude with corresponding results of day-night asymmetry and energy spectra of solar neutrino rates together with a confirmation of the large mixing angle solution by the long baseline reactor experiment KAMLAND [16] would identify a single point in the large mixing angle MSW solution and provide a strong hint for this scheme.

It should be stressed, that a large portion of the 99 % C.L. favored region extends to large $\Delta m^2_{\odot}$ allowing for effective neutrino Majorana masses well above 10^{-2} eV even in the hierarchical case.

If the less favored QVO-LOW solution is realized in solar neutrinos, U_{e2} is close to maximal but the mass of the second state is tiny. In these cases the main contribution to $\langle m\rangle$ comes from m_3:

$$\langle m\rangle \simeq m_{ee}^{(3)} = \frac{1}{4}\sqrt{\Delta m^2_{atm}}\sin^2 2\theta_{ee}, \qquad (11)$$

where $\sin^2 2\theta_{ee} = 4U^2_{e3}$ denotes the mixing angle restricted in disappearance experiments. The situation is illustrated in fig. 4. Here lines of constant $\langle m\rangle$

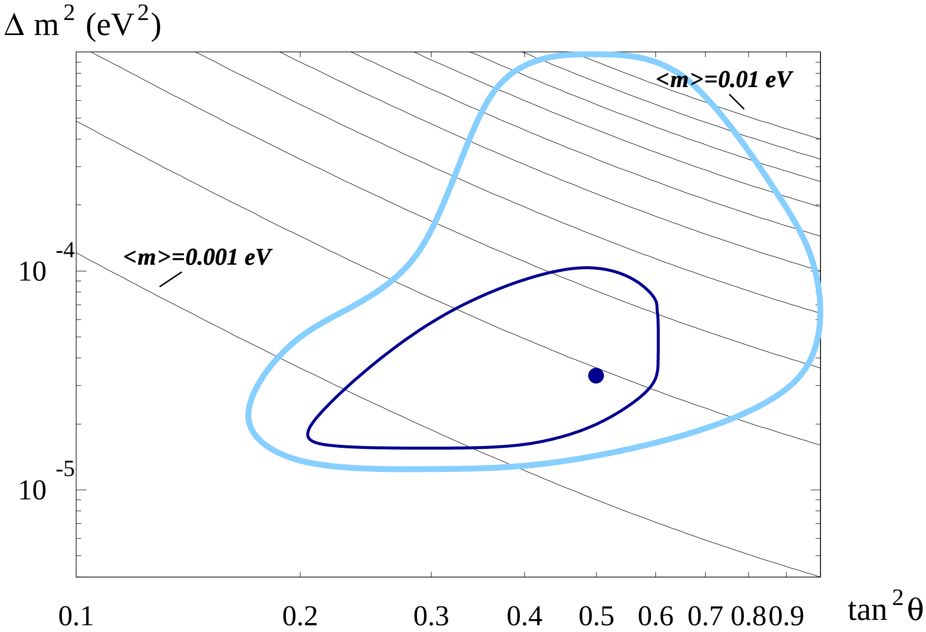


Fig. 3. Double beta decay oberservable $\langle m\rangle$ and oscillation parameters: The case for the MSW large mixing solution of the solar neutrino deficit, where the dominant contribution to $\langle m\rangle$ comes from the second state, shown are lines of constant $\langle m\rangle$. The inner and outer closed line show the regions allowed by present solar neutrino experiments with 90 % C.L. and 99 % C.L., respectively. Complementary informations can be obtained from double beta decay, the search for a day-night effect and spectral distortions in future solar neutrino experiments as well as a disappearance signal in KAMLAND.

are shown as functions of the oscillation parameters Δm^2_{13} and $\sin^2 2\theta_{ee}$. The shaded areas show the mass $m_3 \simeq \sqrt{\Delta m^2_{13}}$ favored by atmospheric neutrinos with the horizontal line indicating the best fit value. The region to the upper right is excluded by the nuclear reactor experiment CHOOZ [15], implying $\langle m\rangle < 2\cdot 10^{-3}$ eV in the range favored by atmospheric neutrinos. Obviously in this case only the 10 ton GENIUS experiment could observe a positive $0\nu\beta\beta$ decay signal. A coincidence of such a measurement with a oscillation signal at MINOS and a confirmation of the solar QVO-LOW MSW oscillations by solar neutrino experiments would be a strong hint for this scheme.

3 Degenerate Scenarios

In degenerate schemes (fig. 5)

$$m_1 \simeq m_2 \simeq m_3 \gtrsim 0.1\mathrm{eV} \tag{12}$$

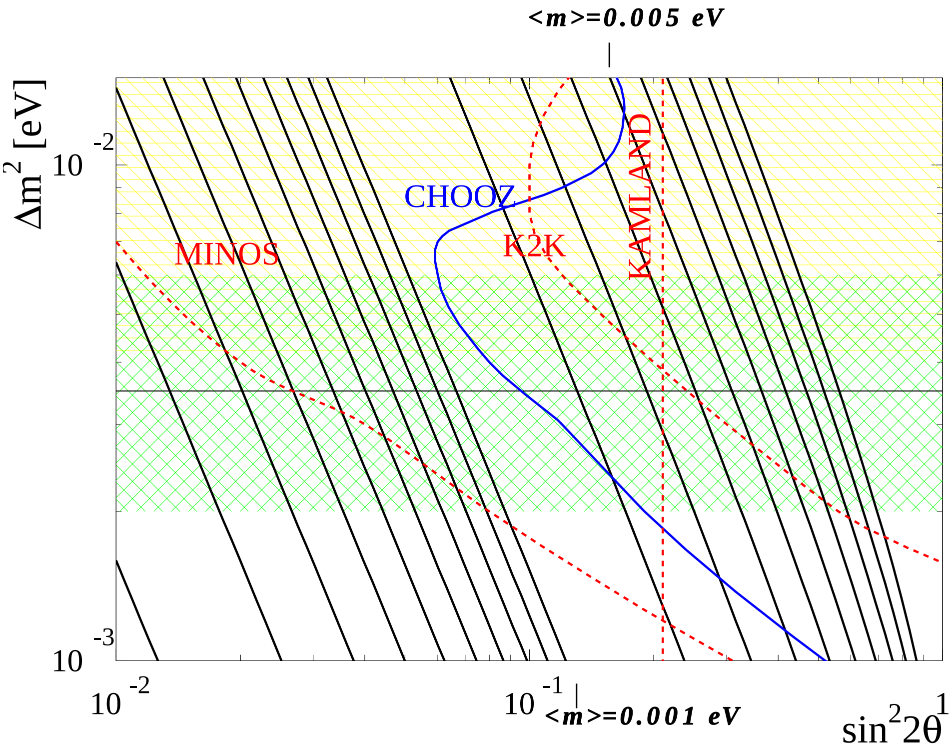


Fig. 4. Double beta decay observable $\langle m \rangle$ and oscillation parameters: The case of hierarchical schemes with the QVO-LOW solution. Shown is the dominant contribution of the third state to $\langle m \rangle$ which is constrained by the CHOOZ experiment, excluding the region to the upper right. Further informations can be obtained from the long baseline project MINOS and future double beta decay experiments [1].

neutrinos still may be of cosmological relevance. Neutrinos with an overall mass scale of a few eV could play an important role as "hot dark matter" component of the universe. When structures were formed in the early universe, overdense regions of (cold) dark matter provide the seeds of the large scale structure, which later formed galaxies and clusters. A small "hot" (relativistic) component could prevent an overproduction of structure at small scales. Since structures redshift photons, this should imply also imprints on the cosmic microwave background (CMB), which could be measured by the future satellite experiments MAP and Planck [17]. While this option of cold-hot-dark-matter cosmology has been disfavored by models including a cosmological constant, as supported by the supernova cosmology project, a new motivation for degenerate models with a less large mass scale may come from the Z-burst interpretation of ultra high energy cosmic rays (UHECRs). In this model UHECRs are understood as the decay products of a resonant annihilation process of high energetic neutrinos with the relic neutrino background [19]. Since the neutrino mass scale is related

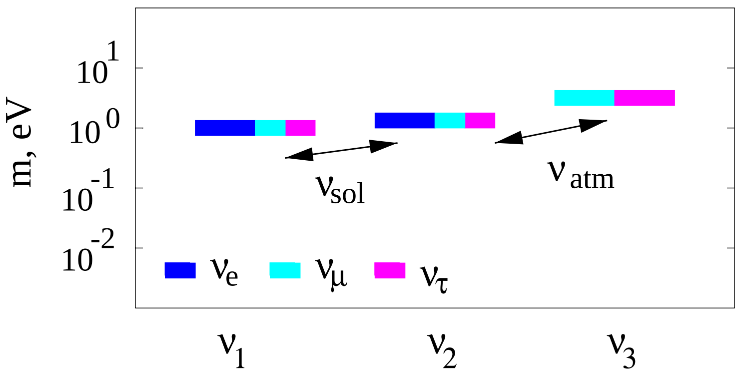


Fig. 5. Neutrino masses and mixings in the degenerate scheme.

to the UHECR energy and relic neutrino clustering on galactic scales may turn out to be a necessary ingredient of the model, an absolute neutrinos mass scale of $\sim 0.1-1$ eV is predicted in this context [19,20].

In degenerate schemes the mass differences are not significant. Since the contribution of m_3 is strongly bounded by CHOOZ again, the main contributions to $\langle m \rangle$ come from m_1 and m_2, which may cancel as an effect of the unknown Majorana CP-phases. The relative contributions of these states depend on their admixture of the electron flavor, which is determined by the solution of the solar neutrino deficit. Then the effective neutrino mass becomes

$$m_{min} < \langle m \rangle < m_1 \tag{13}$$

with

$$\begin{aligned} \langle m \rangle_{min} &= (\cos^2\theta_\odot - \sin^2\theta_\odot)\ m_1 \\ &= \frac{1-\tan^2\theta_\odot}{1+\tan^2\theta_\odot}\ m_1 . \end{aligned} \tag{14}$$

This implies

$$\langle m \rangle = (0.25-1)\cdot m_1 \tag{15}$$

for the large mixing angle solution and

$$\langle m \rangle = (0.1-1)\cdot m_1 \tag{16}$$

for the QVO-LOW solution, where the range allowed corresponds to possible values of the unknown Majorana CP-phases. It should be stressed that this way an upper bound on the mass scale of the heaviest neutrino can be deduced from the recent limit on $\langle m \rangle$. For the LMA solution we obtain $m_{1,2,3} < 1$ eV, implying $\sum_i m_i < 3eV$. For the QVO-LOW solution we obtain $m_{1,2,3} < 3$ eV, implying $\sum_i m_i < 9$ eV.

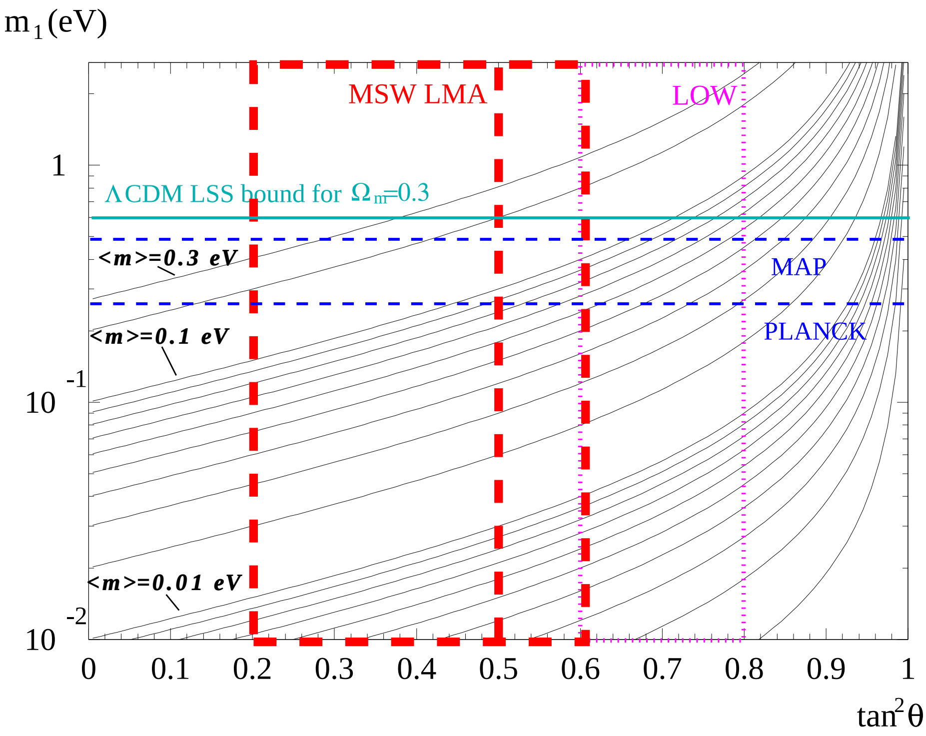


Fig. 6. Double beta decay oberservable $\langle m \rangle$ and oscillation parameters: The case for degenerate neutrinos. Plotted on the axes are the overall scale of neutrino masses m_0 and the mixing $\tan^2 \theta_\odot$. The dashed boxes indicate the 90 % C.L. allowed regions for the large mixing angle (thick dashes, bestfit indicated also) and LOW-QVO solution (thin dashes). Allowed values for $\langle m \rangle$ for a given m_0 correspond to the regions between m_0 and the corresponding curved line. Also shown is a cosmological bound obtained from a fit to the CMB and large scale structure and the expected sensitivity of the satellite experiments MAP and Planck [17].

In fig. 6 lines of constant double beta decay observables (solid curved lines) as functions of the solar mixing are shown together with information from cosmological observations about the overall mass scale (horizontal lines). Shown is the bound $m_j < 0.6$ eV for each of three degenerate neutrinos and for $\Omega_m = 0.3$ at 95 % C.L., obtained from a combined fit to the CMB and large scale structure (LSS) data (The constraint becomes $\sum_j m_j < 5.5$ eV for arbitrary values of Ω_m). Also shown are the expected sensitivities of MAP and Planck to a single neutrino state, 0.5 eV and 0.25 eV, respectively, including polarization data [17].

A coincidence of the absolute mass scale reconstructed from double beta decay and neutrino oscillations with a direct measurement of the neutrino mass in tritium beta decay spectra [21] or its derivation from cosmological parameters determined from the CMB in the satellite experiments MAP and Planck

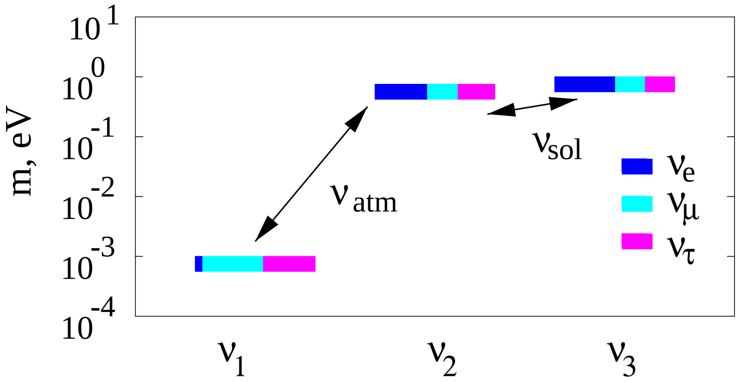


Fig. 7. Neutrino masses and mixings in the scheme with inverse hierarchy.

and future LSS surveys would prove this scheme to be realized in nature. To establish this triple evidence however is difficult due to the restricted sensitivity of the latter approaches. Future tritium experiments aim at a sensitivity down to $\mathcal{O}(0.1$ eV) and MAP and Planck have been estimated to be sensitive to $\sum m_\nu = 0.5 - 0.25$ eV. Thus for neutrino mass scales below $m_0 < 0.1$ eV only a range for the absolute mass scale can be fixed by solar neutrino experiments and double beta decay.

The same conclusions are true for partially degenerate schemes,

$$m_1 \simeq m_2 \ll m_3, \tag{17}$$

keeping in mind that in these cases only the heaviest neutrino affects cosmology. The mass range for partial degeneracy is $m_1 \sim 0.01 - 0.1$ eV

4 Inverse Hierarchy

A further possibility is an inverse hierarchical spectrum (fig. 7)

$$m_3 \simeq m_2 \gg m_1 \tag{18}$$

where the heaviest state with mass m_3 is mainly the electron neutrino, now.

Its mass is determined by the atmospheric neutrinos, $m_3 \simeq \sqrt{\Delta m^2_{atm}}$, implying

$$\sqrt{\Delta m^2_{atm}} \frac{1 - \tan^2 \theta_\odot}{1 + \tan^2 \theta_\odot} < \langle m \rangle < \sqrt{\Delta m^2_{atm}}. \tag{19}$$

For both the large mixing MSW or QVO-LOW solution cancellations of the two heavy states become possible and $\langle m \rangle = (1 - 7) \cdot 10^{-2}$ eV, $\langle m \rangle = (0.4 - 7) \cdot 10^{-2}$ eV, respectively. A test of the inverse hierarchy is possible in matter effects of neutrino oscillations. For this case the MSW level crossing happens for antiparticles rather than for particles. Effects could be observable in long baseline experiments and in the neutrino spectra of supernovae [22]. In fact a recent analysis [23] of SN1987A obtains a strong indication that the inverted mass hierarchy is disfavored unless U_{e1} is large.

5 Transition Regions

In fig. 8 we show the dependence of the individual contributions $m_{ee}^{(i)}$ to $\langle m \rangle$ on m_1, for different values of mixing within the LMA solution. Panel a)-c) correspond to the small mixing bound, best fit and large mixing bound of the 90 % C.L. allowed region, respectively. For $m_{ee}^{(3)}$ only the upper bound is used; the two other lines represent possible values of $m_{ee}^{(1)}$ and $m_{ee}^{(2)}$ for the specific neutrino mixing parameters. We show also the maximal and the minimal possible values of $\langle m \rangle$.

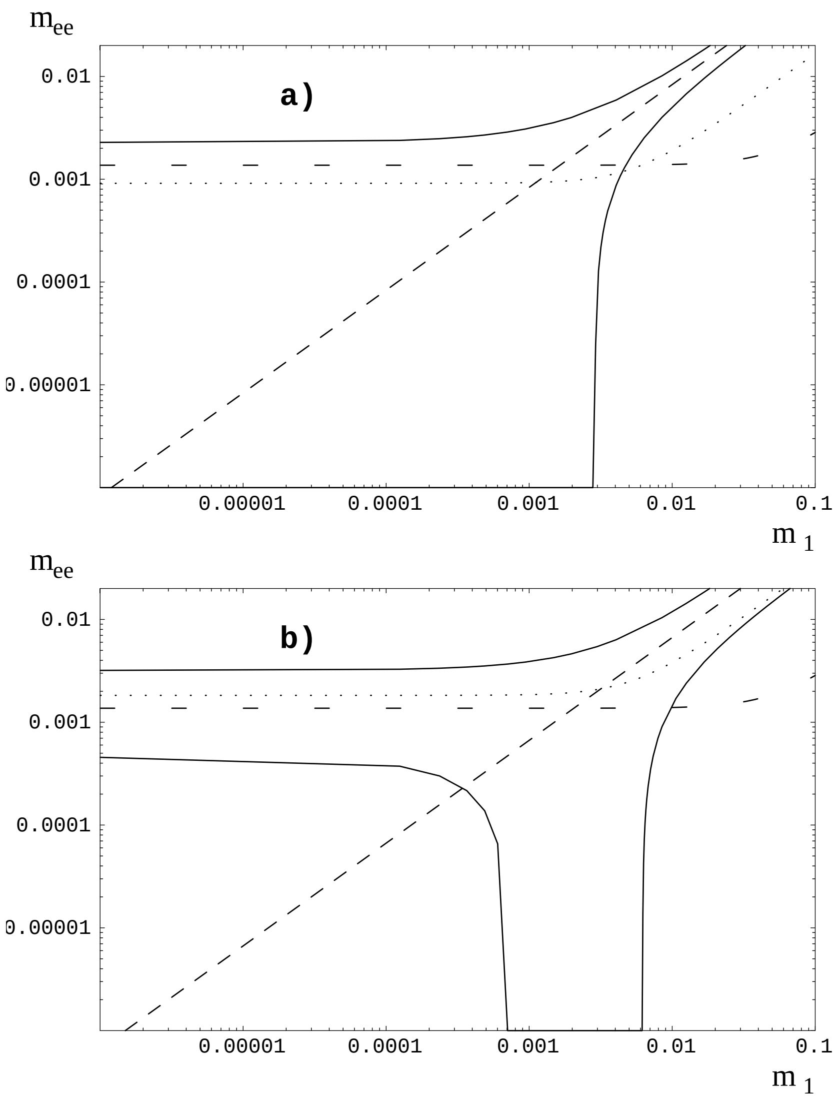
The upper bounds on $\langle m \rangle$ as functions of m_1 have a similar dependence for all the cases. The lower bound in the hierarchical region ($m_1 < 10^{-3} - 10^{-2}$ eV) crucially depends the solar mixing angle. If the solar mixing is sufficiently large the contribution from m_2 dominates and no cancellation is possible even for maximal possible $m_{ee}^{(3)}$ (figs. 8 b,c)). In contrast, for a lower $\sin^2 2\theta_\odot$ the cancellation can be complete so that no lower bound appears (see fig. 8 a)).

In the region of $m_1 \simeq 10^{-3}$ eV all states contribute with comparable portions to $\langle m \rangle$, thus cancellation is possible and no lower bound exists.

For larger values of m_1 the first and the second state give the dominating contributions to $\langle m \rangle$ and the increase of m_3 does not influence significantly the total $\langle m \rangle$. In this case the mass $\langle m \rangle$ is determined by m_1 and $\theta_\odot$ and a larger $\sin^2 2\theta_\odot$ implies a larger possible range of $\langle m \rangle$ for a given m_1, reflecting the uncertainty of unknown Majorana CP-phases.

6 Conclusions

Neutrinoless double beta decay and neutrino oscillations provide complementary pieces to the solution of the neutrino mass puzzle. Correlations of the oscillation parameters and the effective neutrino Majorana mass $\langle m \rangle$ have been discussed in various scenarios favored by recent neutrino oscillation data. The new Super-Kamiokande data presented at the *Neutrino2000* conference improve the prospects of a positive signal in double beta decay. Already now an upper bound for the absolute neutrino mass scale of $m_{1,2,3} < 3$ eV (LOW-QVO) or $m_{1,2,3} < 1$ eV (LMA) has been obtained, being competitive with the recent tritium decay bound [21]. A summary of future perspectives is given in fig. 9, where the size of the bars corresponds to the uncertainty in mixing angles and the unknown Majorana CP-phases. As is obvious from the figure, future double beta decay projects may be able to test all scenarios but the hierarchical spectrum with solar neutrino QVO-LOW solution. One should keep in mind here, that the QVO-LOW solution is disfavored in an analysis of the supernova 1987A [7]. Depending on the value of $\langle m \rangle$ obtained in the future, the follwing conclusions can be drawn.



- For $\langle m \rangle > 0.1$ eV the neutrino mass spectrum is degenerate. An allowed region for the absolute mass scale in the neutrino sector can be obtained. Its size depends on the magnitude of mixing of the solar neutrinos. If the mixing is large, the uncertainty can be up to a factor of 10, if the mixing is small, it will be less than a factor of two. For the MSW bestfit it will be about a factor of three. A crucial contribution may come from KAMLAND, which has been estimated to fix $\sin^2 2\theta_\odot$ within ± 0.1 with three years of accumulated data [16].

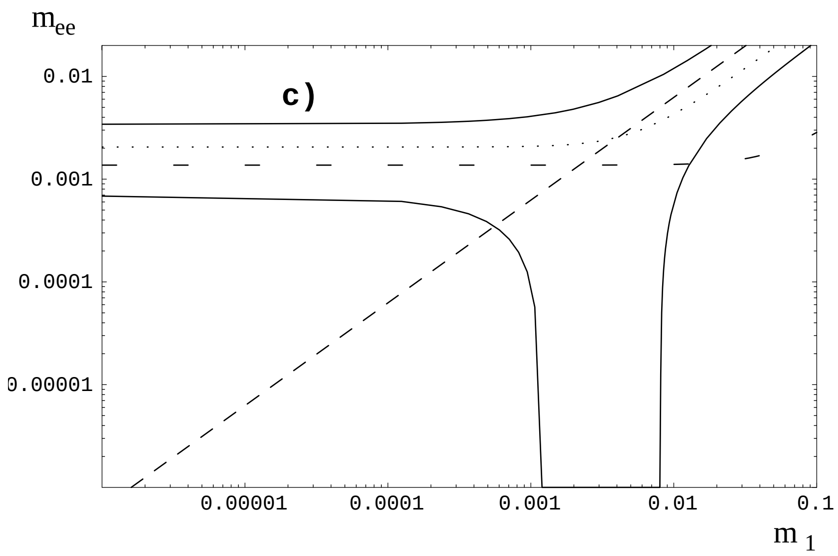


Fig. 8. $\langle m \rangle$ (eV) as a function of m_1 (eV) for three-neutrino mixing. Shown are the contributions $m_{ee}^{(1)}$ (dashed), $m_{ee}^{(2)}$ (dotted) and $m_{ee}^{(3)}$ (interrupted dashes). The solid lines correspond to $\langle m \rangle_{max}$ and $\langle m \rangle_{min}$ and show the allowed region for $\langle m \rangle$. Panels a)-c) correspond to the cases for $U_{e2}^2 = 0.17$, $U_{e2}^2 = 0.33$, and $U_{e2}^2 = 0.38$, i.e. the small mixing bound, best fit and large mixing bound of the 90 % C.L. level LMA solution. The mixing of the third state is varied from zero to its upper bound, $U_{e3}^2 = 2.5 \cdot 10^{-2}$.

- For $\langle m \rangle \simeq 0.01 - 0.1$ eV the neutrino mass spectrum can be degenerate, partial degenerate or inverse hierarchical. Again an allowed region for the absolute mass scale can be fixed, provided the character of hierarchy (direct/inverse) can be established from neutrino oscillations in matter. A recent analysis comes to the conclusion, that the inverse hierarchy is disfavored already for not too large values of U_{e3}.
- For $\langle m \rangle \simeq 0.001 - 0.01$ eV the neutrino mass spectrum can be partial degenerate or inverse hierarchical. The conclusions above remain valid.
- For $\langle m \rangle < 0.001$ eV the spectrum is hierarchical.

In view of this potential the realization of future double beta decay projects is highly desirable. We are entering an exciting decade.

7 Acknowledgement

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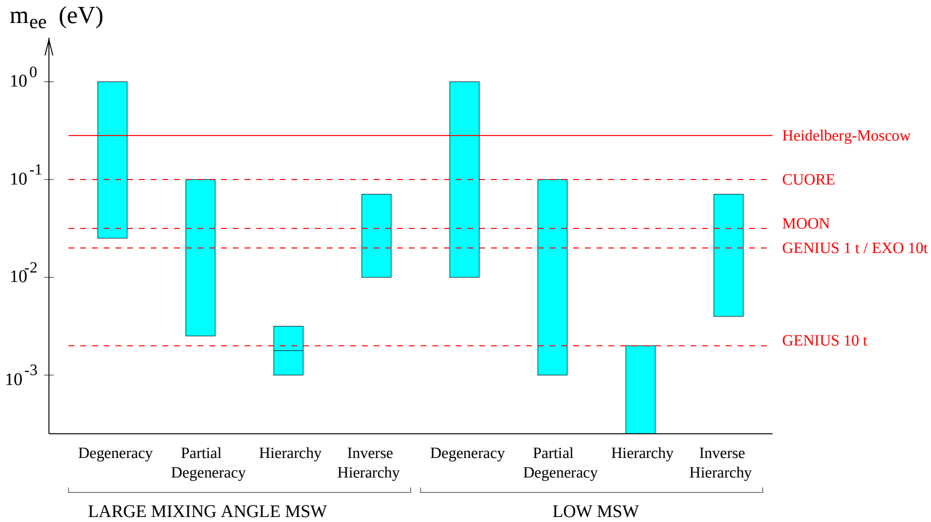

Fig. 9. Summary of expected values for $\langle m \rangle$ in the different schemes discussed in this paper. The size of the bars corresponds to the uncertainty in mixing angles and the unknown Majorana CP-phases. The expectations are compared with the recent neutrino mass limits obtained from the Heidelberg–Moscow [10] experiment as well as the expected sensitivities for the CUORE [11], MOON [12], EXO [13] proposals and the 1 ton and 10 ton proposal of GENIUS [14].

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